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Status of Neutrino Physics Experiments

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I will present a review of some relevant results from neutrino physics experiments since FPCP2009 with an emphasis on oscillations and the ability to measure or limit the mixing angle θ_{13}.

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1. Terrestrial neutrinos

The Borexino experiment reported the observation of geo-neutrinos [1]. Borexino is located in LNGS with a 3800 m.w.e (meters of water equivalent) overburden. The neutrino target is 278 tons of high-purity liquid scintillator in a spherical, 8.5m diameter, nylon vessel. It is surrounded by 890 tons of buffer in a 11.5 m diameter outer nylon vessel and 13.7 m diameter stainless steel shell. The target is viewed by 2212 8" PMTs. The stainless steel vessel is in a water-filled tank viewed by an additional 208 8" PMTs. The exposure for the geo-neutrino observation was 253 ton-years.

Geo-neutrinos are $\bar{\nu}_e$ produced by β decays of ^{40}K and nuclides in the ^{238}U and ^{232}Th chains. Geo-neutrinos provide a direct measure of the abundance and distribution of radioactive elements in the Earth, and would permit an assessment of the radiogenic contribution of the Earth's heat balance. In Borexino, the $\bar{\nu}_e$ are detected via the inverse beta decay (IBD) reaction $\bar{\nu}_e p \to e^+ n$ that provides a distinctive coincidence signature. The prompt energy from the positron is related to the incident $\bar{\nu}_e$ energy, $E_{\rm vis} \approx E_\nu - 0.78$ MeV, and the delayed capture of the neutron on hydrogen produces a 2.22 MeV γ with a characteristic capture time of $\tau \sim 256$ μs. Only ^{238}U and ^{232}Th chains produce $\bar{\nu}_e$ above the IBD threshold up to $\sim$2.5 MeV in positron energy. European reactors produce a background of $\bar{\nu}_e$ that extends to $\sim$7 MeV in e^+ energy. Non-$\bar{\nu}_e$ background is dominated by cosmogenic sources and is suppressed by vetoing on detected cosmic rays. The total estimated non-$\bar{\nu}_e$ background is 0.31 ± 0.05 events. The fitted number of geo- and reactor-neutrino events is $9.9^{+4.1}_{-3.4}$ and $N_{\rm reac} = 10.7^{+4.3}_{-3.4}$, respectively, and the number of geo-neutrinos is non-zero at 99.997% CL. The measured geo-neutrino rate of $3.9^{+1.6}_{-1.3}$ events/(100 ton·year) is consistent with the Maximal Radiogenic Earth model that postulates that all terrestrial heat is produced exclusively by radiogenic elements.

2. Solar neutrinos

2.1 Borexino

Borexino has also made a measurement of the ^{8}B flux of solar neutrinos [2]. The neutrinos are detected by elastic scattering (ES) on atomic electrons so that the measurement is mainly sensitive to ν_e as the $\nu_e e$ ES cross-section is 6.3 times larger than the ES $\nu_{\mu,\tau} e$ cross-sections. A 3 MeV threshold limits background from radioactivity. Background is dominated by cosmogenic production of unstable isotopes from ^{12}C as $\sim$4300 muons/day deposit energy in the Borexino inner detector. Short-lived isotopes are suppressed by a $>$ 6.5s veto after a muon. Longer-lived isotopes (^{10}C, ^{11}Be) are suppressed and subtracted. From 345.5 live days with a 100t fiducial mass, 75 ± 13 ^{8}B solar ν candidates remain, consistent with solar models that predict 86 ± 10 or 73 ± 7 events.

2.2 Sudbury Neutrino Observatory (SNO)

The SNO neutrino target is 1000 tons of heavy water, D_2O, in a 12 m diameter, 5 cm thick acrylic vessel viewed by 9456 20-cm PMTs mounted on a 18 m diameter steel frame in a 8400 t H_2O buffer located in the Creighton Mine, Canada, with a 5890 m.w.e. overburden. The heavy water target enables detection of solar neutrino interactions by charged current (CC), elastic scattering (ES) and neutral current (NC) process:

CC $\nu_e + d \to p + p + e^-$

ES $\nu_x + e^- \to \nu_x + e^-$

NC $\nu_x + d \to p + n + \nu'_x$

and allowed definitive resolution of the solar neutrino problem [4]. SNO recently reanalyzed their Phase I and Phase II data with an improved, Low-Energy-Threshold Analysis(LETA) [3]. In Phase II, 2 tons of NaCl was added to the heavy water to improve neutron detection for NC events. The LETA improvements included the lowering of the visible energy threshold to 3.5 MeV from $\sim$5 MeV, a more sophisticated energy reconstruction that narrowed the resolution by $\sim$6% and reduced the low-energy backgrounds by $\sim$60%, better background rejection cuts and better data quality cuts. Combining the NC, CC and ES measurements for LETA yields the most precise measurement of the solar ^{8}B neutrino flux, $\Phi(^8\mathrm{B}) = (5.046^{+0.159}_{-0.152}(\mathrm{stat})^{+0.107}_{-0.123}(\mathrm{syst})) \times 10^6/\mathrm{cm}^2/\mathrm{s}$. When the SNO LETA is combined with KamLAND and other solar neutrino results in a three neutrino fit, the solar neutrino parameters are determined to be $\theta_{12} = 34.06^{+1.16^\circ}_{-0.84}$ and $\Delta m^2_{21} = (7.59^{+0.20}_{-0.21}) \times 10^{-5}$ eV^2 with $\sin^2\theta_{13} = (2.00^{+2.09}_{-1.63}) \times 10^{-2}$ or $\sin^2\theta_{13} < 0.057$ at 95% CL.

3. Extraterrestrial Neutrinos

Super-Kamiokande (SK) is a cylindrical water Cherenkov detector 39 m in diameter and 14 m high, filled with 50kt of ultra pure water, with a 2700 m.w.e. overburden. The main detector volume is viewed by $\sim$11000 20" PMTs for $\sim$40% photocathode coverage. SK observes neutrinos from solar, atmospheric and accelerator sources. Muons and electrons are distinguished and measured using the pattern of observed Cherenkov light. A recent SK analysis [5] attempts to limit θ_{13}, determine whether θ_{23} is greater or less than 45° and resolve the mass hierarchy all via sub-leading effects in atmospheric neutrinos. The analysis results in limits of $\sin^2\theta_{13} < 0.04(0.09)$ for the normal (inverted) hierarchy and $0.407 < \sin^2\theta_{23} < 0.583$ at 90% CL with essentially no discriminating power on the mass hierarchy.

4. Artificial Neutrinos

The MINOS experiment using an accelerator-produced beam with a most probable energy of $\sim$3 GeV composed of 93% ν_μ, 6% $\bar{\nu}_\mu$, and 1% $\nu_e + \bar{\nu}_e$. The beam is directed from Fermilab towards the Soudan mine. The MINOS near (ND) and far detector (FD) are 1 and 735 km from the neutrino production target, at depths of 100 and 700 m, with masses of 0.98 kt and 5.4 kt, respectively. The detectors are are alternating layers of magnetized steel (2.54cm, 1.4 X_0) and planes of scintillator strips (4.1cm wide).

MINOS searches for $\nu_\mu \to \nu_e$ appearance to measure $\sin^2 2\theta_{13}$; however, ν_e appearance probability depends not only on θ_{13} but also on the CP-phase δ and the sign of Δm^2_{31} (the mass hierarchy) [6]. This search must discriminate between the electromagnetic shower in CC interactions $\nu_e A \to e^- X$ and the showers produced in NC interactions $\nu A \to \nu X$. There are also other backgrounds due to ν_μ CC interactions with a short μ track, the intrinsic ν_e in the beam and $\nu_\mu \to \nu_\tau$ oscillations. Eleven shower shape variables are combined in an artificial neural network.

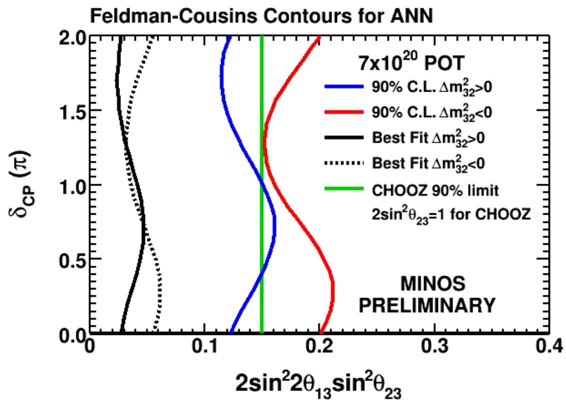

Figure 1: Values of $2\sin^2 2\theta_{13}\sin^2\theta_{23}$ and δ that produce a number of candidate events in the Far Detector consistent with the observation for the normal and inverted hierarchy. The best fit is represented by the black lines. The green line is the CHOOZ limit drawn for $\Delta m^2_{32} = 2.43\times 10^3$ eV^2 and $\sin^2\theta_{23} = 1.0$.

The ND is utilized to obtain a background sample than is extrapolated to predict the background at the FD. Fifty-four events are observed at the FD compared to a total expected background of 49.1 ± 7.5 (36 NC, 6 ν_μ CC, 5 beam ν_e, 2 ν_τ CC) [7]. Figure 4 shows the resulting contours in the $2\sin^2 2\theta_{13}\sin^2\theta_{23}$ *vs.* δ plane.

5. Global analysis

A global analysis in the 3 neutrino framework is performed by Gonzalez-Garcia, Maltoni and Salvado [8] that use Borexino, SNO LETA, SK and MINOS results described in this paper. The fit also includes results of the Chlorine, Gallex/GNO and SAGE radiochemical experiments, SuperK solar neutrino results and KamLAND. It includes uncertainties due to ν_e capture cross-section in gallium and in the solar model (low- and high-metallicity). Similar results are found by other analyses [9][10].

The fit results are $\Delta m^2_{21} = (7.59^{+0.61}_{-0.69})\times 10^{-5}$ eV^2, $\theta_{12} = (34.4^{+3.2}_{-2.9})^\circ$, $\theta_{23} = (42.8^{+10.7}_{-7.3})^\circ$, $\theta_{13} \leq 12.5^\circ$, and $\Delta m^2_{31} = (-2.36\pm 0.37)\times 10^{-3}$ eV^2 or $(+2.46\pm 0.37)\times 10^{-3}$ eV^2 for the two possible mass orderings. The quoted uncertainties and limits are at 3σ. The results are also shown in Figure 2.

References

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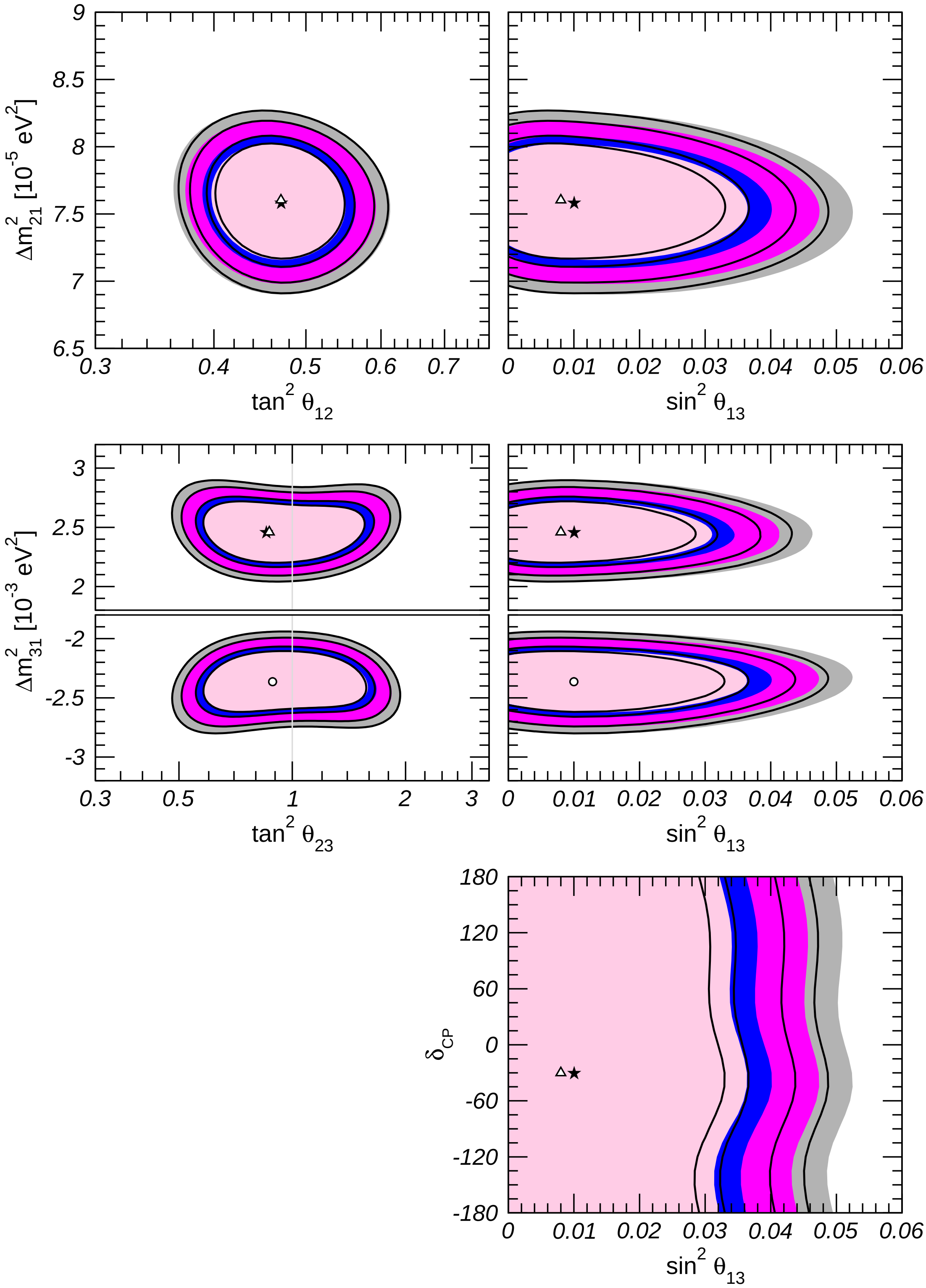

Figure 2: Results of the global fit [8]. The different contours correspond to 90%, 95%, 99% and 3σ CL. The full regions are for the high-metallicity solar model and the void regions are for the low-metallicity solar model.

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